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Functional Recovery and Muscle Properties After Stroke: A Preliminary Longitudinal Study

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1. Introduction

Almost all patients with stroke experience a certain degree of functional recovery within the first six months after stroke. Most recovery of motor and functional performance is seen in the first month after stroke (Gray et al., 1990; Duncan et al., 1992, 1994; Jorgensen et al., 1995; Horgan & Finn, 1997; Kong et al., 2011) but improvement may continue as long as 6–12 months after stroke (Bonita & Beaglehole, 1988). Verheyden et al. (2008) observed most improvement for trunk, arm, leg and functional recovery from 1 week to 1 month after stroke and then to a lesser extent between 1 and 3 months after stroke. Only small, not statistically significant changes could be seen between 3 and 6 months after stroke, indicating that a "plateau phase" was already reached at 3 months after stroke. Further improvement after 6 months can be expected but is mostly limited (Mayo et al., 1999; Hendricks et al., 2002; Desrosiers et al., 2003; Kwakkel et al., 2004). Six months after stroke, only 60% of people with initial hemiparesis have achieved functional independence in simple activities of daily living such as toileting and walking short distances (Mayo et al., 1999; Patel et al., 2000). However, improvements in activities of daily living may continue despite stable deficits at the level of impairment. This is suggestive of further behavioral adaptation or compensation. Rehabilitation is devoted to enlarge and precipitate this functional recovery in order to improve quality of life after stroke (Gresham et al., 1995). Therefore, rehabilitation programs adapted to objectives as allowed by the state of the neuromuscular system are important.

Many daily activities, especially locomotion, require sufficient function of thigh muscles. A number of studies reported that lower extremity muscles are weaker in patients with stroke compared to healthy controls (Newham & Hsiao, 2001; Bohannon, 2007b; Sullivan et al., 2007; Horstman et al., 2008). Furthermore, the inability to generate normal amounts of force has been suggested to be the major limitation of physical activity (Mercier & Bourbonnais, 2004; Ada et al., 2006). More specific, intrinsic strength capacity as well as the ability to maximally activate the knee extensors correlate strongly with functional performance (daily activities) in patients with stroke (Bohannon, 1988, 1989; Corrigan & Bohannon, 2001; Kim & Eng, 2003; Bohannon, 2007b; Patterson et al., 2007; Horstman et al., 2008). In addition, a recent study showed a significant association between paretic lower limb strength and balance both *cross-sectionally* in *acute* patients with stroke as well as *longitudinally* in *post-acute* patients (van Nes et al., 2009).

Besides a reduction in maximal muscle strength, the ability to generate torque as fast as possible, is also impaired after stroke (Horstman et al., 2010; Bohannon & Walsh, 1992; Gerrits et al., 2009). Rate of torque development is an important determinant of e.g. risk of falling and (again) for controlling balance (Shigematsu et al., 2006; Pijnappels et al., 2008). Recent work from our group has shown lower maximal rates of torque development during electrically stimulated (Horstman et al., 2010; Gerrits et al., 2009) as well as during voluntary (Horstman et al., 2010) contractions of the paretic and non-paretic knee-extensors. Decreased ability to rapidly develop knee extension torque contributes more to lower walking speed after stroke than does maximal strength (Pohl et al., 2002).

In summary, there is clear evidence that difficulties in executing daily tasks in patients with stroke are related to both impaired strength and speed of paretic and/or non-paretic muscles. Nevertheless, most studies are performed at one point in time (Kim & Eng, 2003; Mercier & Bourbonnais, 2004; Ada et al., 2006; Bohannon, 2007b; Patterson et al., 2007; Horstman et al., 2008). It is not fully elucidated whether the improvements in functional performance at the activity level of patients with stroke during rehabilitation relate to changes in specific contractile function of the thigh muscles. Therefore, the present study reports on *longitudinal* changes in functional performance in a group of patients with stroke during the first year after stroke. Furthermore, it is determined whether these changes relate to alterations in strength and speed characteristics of the paretic and non-paretic thigh muscles and voluntary activation capacity of patients with stroke.

2. Methods

2.1 Subjects

A total number of fourteen patients were included in the study. Patients (characteristics: see Table 1), all with first-ever stroke and a hemiparesis of the lower extremity, entered the study on average 3.5 months after stroke and 2 months after admission in the rehabilitation centre (t=0). Data on muscle function in relation to functional performance of these patients at t=0 are reported elsewhere (Horstman et al., 2008). They were invited for measurements again 3 (n=8), 6 (n=5) and 12 (n=3) months after the first measurement (follow-up (F)1, F2 and F3 respectively). Because of drop-out of a number of subjects, data will be largely descriptive. Before participation, each subject was thoroughly informed about the procedures, completed a health questionnaire and signed an informed consent.

The exclusion criteria were medical complications (such as unstable cardiovascular problems), severe cognitive and/or communicative problems preventing understanding verbal instructions or limiting performance of the requested tasks (e.g. aphasia, hemineglect) and contra-indications for electrical stimulation (unstable epilepsy, cancer, skin abnormalities and pacemaker). The project carried the approval of the institutional review board (Medical Ethical Committee) of the VU University Medical Centre, Amsterdam, The Netherlands.

Subject no.	Gender	Age (yrs)	Weight (kg)	Height (cm)	Time after stroke (days)	Time after admission (days)	Side of lesion (Left/ Right)	Ischaemic/ Hemorrhage	Last measurement
1	Male	65	70	172	189	29	R	I	F3
2	Male	61	89	172	84	67	L	H	F3
3	Male	61	80	182	52	76	L	I	F3
4	Male	52	79	172	87	55	L	H	F2
5	Male	55	81	177	167	145	R	I	F2
6	Male	56	80	168	77	41	L	I	F1
7	Female	26	63	170	110	52	R	I	F1
8	Female	62	60	168	55	61	R	I	F1
9	Female	61	40	150	123	76	L	H	t=0
10	Male	57	69	180	170	70	R	I	t=0
11	Female	64	74	170	117	90	L	I	t=0
12	Male	45	80	190	79	35	R	H	t=0
13	Male	67	100	190	157	114	R	H	t=0
14	Male	58	83	178	56	29	R	I	t=0

Table 1. Subject characteristics.

2.2 Experimental set-up

Body function and activity-participation level were assessed with different clinical tests ('functional performance' tests). In addition, muscle function characteristics of the knee-extensors and -flexors were assessed in both limbs. The measurements were spread over four different days with at least one day of rest in between.

2.3 Experimental procedures

2.3.1 Functional performance tests

The following tests were performed by the subjects under supervision of a physiotherapist (except for the Rivermead Mobility Index, which was carried out by one of the researchers):

- *Berg Balance Scale (BBS)* assesses sitting and standing balance and exists of 14 test-items, scored on an ordinal 5-point scale (0-4). It gives an estimation of the chance that patients with stroke will fall (Berg et al., 1989, 1992, 1995).
- *Brunnstrom Fugl-Meyer (FM), lower extremity,* is a test for evaluation of patellar, knee flexor and Achilles reflexes, flexor and extensor synergies, isolated movements of knee flexor and ankle dorsal flexor function and normal reflex activity of the quadriceps and triceps surae muscles in the paretic lower limb hemiplegic patients (Fugl-Meyer et al., 1975). Maximal possible score is 34.
- *Rivermead Mobility Index (RMI)* comprises a series of 14 questions and one direct observation, and covers a range of activities from turning over in bed to running. It is a measure of mobility disability which concentrates on body mobility (Collen et al., 1991).
- *Timed "get-up-and-*go" test (TUG) requires patients to stand up from a chair, walk 3m, turn around, return, and sit down again. Time to fulfil this test is measured (Podsiadlo & Richardson, 1991). The shorter the time needed to do this test, the better; for all other tests applies the higher the score, the better.

- *10 meter walk test (10m)* is performed at comfortable (self selected) walking speed by patients who are able to walk independent with or without mobility aid and/or orthesis. Time to walk 10m is measured and averaged over three trials (Smith & Baer, 1999). Then, the speed is calculated (10m divided by the average time to walk that 10m).
- *Motricity Index (MI)* evaluates the arbitrary movement activity and maximum isometric muscle force. Possible scores are 0-9-14-19-25-33 at each of the three parts of the test for lower extremities (Demeurisse et al., 1980; Collin & Wade, 1990; Cameron & Bohannon, 2000).
- *Functional Ambulation Categories-score* (*FAC*) evaluates the measure of independence of walking of the patient. Categories are scored on a six-point scale (0-5) (Holden *et al.*, 1984, 1986).

2.3.2 Force measurements

The procedures for the measurements as well as the calculation of variables are described in detail elsewhere (Horstman et al., 2008). Briefly, maximal voluntary and electrically evoked isometric torques of the knee extensors and maximal voluntary isometric torques of the knee flexors were measured while subjects were seated on a custom built Lower EXtremity System (LEXS) (Horstman et al., 2008). The lower leg was strapped tightly to a force transducer just above the ankle by means of a cuff at a knee flexion angle of 60° (0° = full extension). Electrical stimulation, used for the knee extensors only, was applied via two surface electrodes placed over the quadriceps muscles with a computer-controlled constant current stimulator (Digitimer DSH7, Digitimer Ltd., Welwyn Garden City, UK).

2.3.3 Familiarization session

During the familiarization session, measurements were performed with the non-paretic lower limb to check whether the instructions were understood by the subject. After a warming-up (existing of 5 submaximal contractions) subjects were trained to perform maximal isometric knee flexion (MVCf) and extension (MVCe) contractions and fast voluntary knee extensions. Subsequently, the subjects were familiarized with electrical stimulation. During the follow-up measurements, no familiarization session was performed.

2.3.4 Muscle strength and speed

Subjects were asked to maximally generate isometric knee extensions for 3-4 s to determine MVCe. Alternately, MVCfs were performed, as described in Horstman et al. (2008). Thereafter, subjects were asked to perform knee extensions as fast as possible (Horstman et al., 2008) with the command: 3, 2, 1 GO! They were encouraged to reach a peak force of at least 70% of their MVC and were not allowed to make a countermovement (flexion) or have pretension before the fast extension (de Ruiter et al., 2004). The same measurements as performed with the paretic lower limb (PL) were repeated with the non-paretic lower limb (NL), carried out on a separate day. Control subjects just performed one session, with the right leg only.

2.3.5 Triplet stimulation and voluntary activation

A modified super-imposed stimulation technique was used in which electrically evoked triplets (pulse train of three rectangular 200 μs pulses applied at 300 Hz) were used to establish the subjects' capacity to voluntarily activate their muscles (Kooistra et al., 2005). Measurements started with PL in a knee angle of 60° knee flexion. First, stimulation current was increased until supramaximal stimulation was ensured. Next, subjects underwent measurements consisting of a triplet superimposed on the plateau of the force signal of the MVC. Subsequently, these measurements were performed with NL.

2.4 Data analysis of muscle function

MVC torque (Nm) was determined as the peak force from the force plateau multiplied by the external moment arm. MVCe and MVCf were assessed. *Maximal rate of torque development* was defined as the steepest slope of torque development during fast voluntary contractions (MRTDvol) (de Ruiter et al., 2004) and during a pulse train of 80 ms, 300 Hz (MRTDstim). MRTDvol was normalized to MVCe torque in order to correct for the number of parallel muscle fibers ('muscle thickness') to get a fair comparison of contractile speed of muscles between different subjects independent of absolute maximal torques. MRTDstim was therefore expressed as a percentage of 150 Hz torque (obtained at the same stimulation intensity as the 300 Hz pulse train).

Voluntary activation is defined as the completeness of skeletal muscle activation during voluntary contractions and was calculated by means of a modified interpolated twitch technique (Kooistra et al., 2005). *Voluntary activation (%) = [1 – (superimposed triplet/rest triplet)] * 100.* Here the superimposed triplet is the force increment during a maximal contraction at the time of stimulation and the control triplet is that evoked in the relaxed muscle (Shield & Zhou, 2004). Supramaximal *triplet torque* of the relaxed muscle is used as a measure for the maximal (intrinsic) torque capacity of the knee extensors, independent of voluntary activation.

Spearman rank correlations were calculated between changes (Δ, between t=0 and F2) in scores at the tests of functional performance and changes in the 6 muscle variables (MVCe, MVCf, MRTDvol, MRTDstim, triplet and voluntary activation). For the differences over time, shown in Table 2, a Friedman test was used.

3. Results

Not all subjects participated in follow-up sessions. The most important reason given was that travelling to the testing site was too time-consuming. Some experienced the measurements (especially the electrical stimulation and the duration of the experiments) as too uncomfortable. Other patients missed the follow-up measurements due to severe illness. One patient decided to spend the winter abroad. Moreover, data were not complete for some of the patients due to unreliability, e.g. concentration problems (one subject dozed off a few times during the measurements), no force plateau during the MVCs or subjects did not reach 90% of their MVC during the familiarization session. Therefore, the data will be mainly descriptive and hardly any statistical analyses were performed.

3.1 Functional performance

Figure 1 shows the course of the scores of the subjects with stroke at two important (see below, Table 4) tests of functional performance, namely the BBS, a measure of ability-activity level, and at the FM, an impairment (bodily functions) measure developed to assess physical recovery after stroke (Sanford et al., 1993). Because the outcome of most tests of functional performance seemed to plateau at F2 and because F3 values could only be obtained in three subjects, mean values of the five subjects assessed until F2 are presented in Table 2. Data in this table are expressed as median and 1st and 3rd quartile. Overall, the data of the functional performance tests show improvement (except for MI) during the follow-up period.

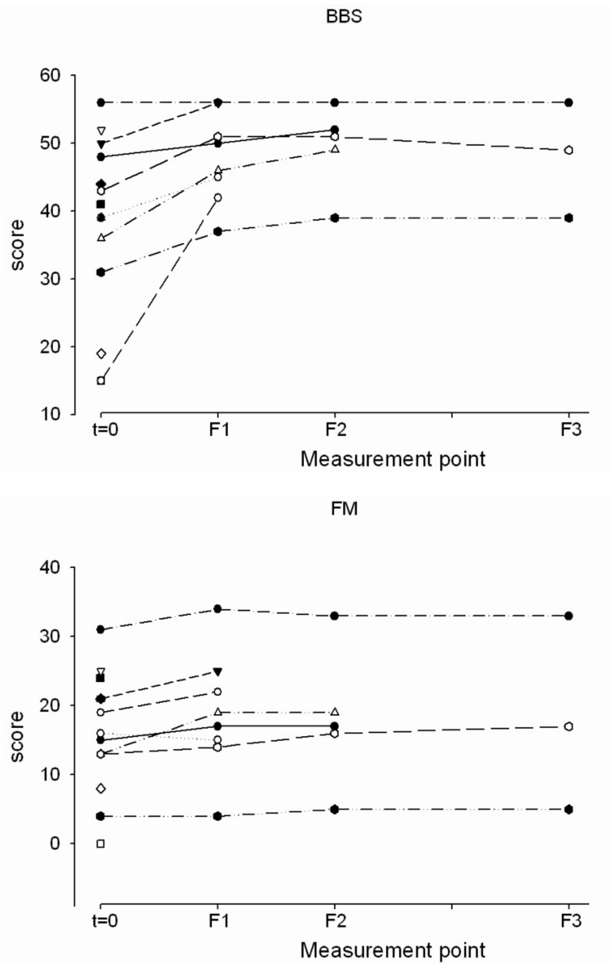


Fig. 1. Course of all individual scores at the Berg Balance Scale (BBS) and Brunnstrom Fugl-Meyer, lower extremity (FM) at 4 measuring times (t=0, F1, F2, F3). Note that t=0 is on average 3.5 months after stroke.

	t=0	F1	F2
BBS	43 (36-48)	50 (46-51)*	51 (49-52)*
MI	42 (39-47)	61 (42-64)	61 (53-61)
FAC	4 (3-4)	5 (4-5)*	5 (5-5)*
RMI	8 (7-8)	13 (12-13)*	13 (12-13)*
FM	13 (13-15)	17(14-19)^	17 (16-10)*
10m (m/s)	0.28 (0.23-0.39))	0.36 (0.35-0.47)^	0.35 (0.30-0.53)*
TUG (s)	43.5 (34.7-49.0)	34.0 (34.0-41.0)	30.1(20.8-38.0)^

* significant improvement (p<0.05) compared with t=0
^ trend (p<0.1) compared with t=0

Table 2. Median values and 1st and 3rd quartiles for the Berg Balance Scale (BBS), Motricity Index (MI), Functional Ambulation Categories-score (FAC), Rivermead Mobility Index (RMI), Brunnstrom Fugl-Meyer (FM), 10 meter walk test (10m) and Timed ''get-up-and-go'' test (TUG) at the 3 measurement points 3.5 months after stroke (t=0) and during follow-up (F)1 and F2 for the five subjects who participated at these three measurement points (n= 5).

3.2 Muscle variables

Data were not complete for reasons explained earlier. Furthermore, it is a general experience that subjects, knowing that a superimposed stimulation will be performed, anticipate upon stimulation and perform less when compared with MVC without stimulation. To minimize this effect, which influences the activation results, only data were used when MVCs with superimposed stimulation were more than 90% of their highest attempt. Therefore, variables of muscle functions in Table 3 show missing values. The zero values are values from subjects who did perform the measurements but were not able to generate force with their paretic lower limb.

There was a substantial variation between subjects with respect to the outcome of the muscle variables at the start of the study (t=0) as well as with respect to the changes in these variables over time (Table 3).

3.3 Correlations between changes in functional performance and muscle function

Table 4 shows the potential relevant correlations (n=4 or 5) with $|\rho|>0.7$ between changes (Δ, i.e., MVCe at F2 minus MVCe at t=0) in scores at tests of functional performance and changes in muscle variables. Figure 2 shows the five significant correlations namely the correlations between ΔMVCf of PL and Δ10m (ρ=0.99, p=0.002, n=5), between ΔMRTDstim of PL and ΔFM (ρ=0.99, p=0.01, n=4), between Δtriplet of PL and ΔFM (ρ=0.90, p=0.04, n=5), between Δtriplet of PL and ΔRMI (ρ=0.92, p=0.03, n=5), and between ΔMVCf of NL and ΔBBS (ρ=0.92, p=0.03, n=5).

4. Discussion

A considerable improvement was found in de scores at the tests of functional performance, especially up to F2. In general also the muscle variables improved over time. Changes in muscle variables of the 5 subjects that were measured at t=0, F1 and F2 were shown to correlate with improvements in tests of functional performance during the first 9 months after stroke.

	Subject	PL t=0	PL F1	PL F2	NL t=0	NL F1	NL F2
MVCe (Nm)	**1**	0	0	0	149	125	145
	2	35	30	63	101	109	130
	3	171	149	186	250	245	255
	4	82	105	132	145	174	156
	5	64	107	137	162	171	246
MVCf (Nm)	**1**	0	0	0	35	13	53
	2	1	0	8	39	60	68
	3	50	51	73	90	92	88
	4	0	0	0	68	60	62
	5	0	0	0	54	71	101
MRTDvol (% $\cdot$ ms^{-1})	**1**	0.00	0.00	0.00	4.16	5.93	5.83
	2	2.03	-	2.59	5.74	-	4.70
	3	7.08	10.53	8.62	9.29	6.44	3.51
	4	3.30	2.87	3.82	4.69	3.77	3.51
	5	5.19	6.27	7.11	9.34	7.92	8.30
MRTDstim (% $\cdot$ ms^{-1})	**1**	10.31	15.51	14.24	12.77	13.24	14.24
	2	5.46	-	11.35	13.78	16.40	16.88
	3	16.77	19.03	21.22	26.28	37.97	30.00
	4	14.13	9.07	-	14.39	13.14	-
	5	9.07	12.07	19.68	8.67	11.44	19.43
Triplet torque (Nm)	**1**	41	42	48	84	84	94
	2	29	-	44	50	52	42
	3	110	101	112	113	112	109
	4	82	104	96	110	115	100
	5	75	90	103	110	115	100
VA (%)	**1**	-	-	-	70	55	69
	2	16	-	57	75	-	85
	3	73	75	79	88	93	91
	4	64	55	55	68	85	73
	5	42	59	75	75	81	80

Table 3. Data on muscle variables for 5 subjects who were measured during the first measurement (t=0) and 3 and 6 months thereafter (F1, F2 respectively) for the non-paretic (NL) and paretic lower limb (PL). Maximal voluntary extension (MVCe) and flexion (MVCf) torque, maximal rate of torque development during voluntary (MRTDvol) and electrically evoked contractions (MRTDstim), triplet torque and voluntary activation (VA).

		BBS	FM	RMI	10m (m/s)	FAC	TUG (s)	MI
PL	MVCe	-	0.843^	0.861^	-	-	-	0.832^
	MVCf	-	-	-	0.985*	-	-	-
	MRTDvol	-	0.750	-	-	-	-	-
	MRTDstim	0.736	0.990*	0.860	-	-	-	0.815
	Triplet	0.827^	0.897*	0.923*	-	-	-	-
	VA	0.710	-	-	-	-	-	-
NL	MVCe	0.745	N.A.	0.833^	-	-	-	-
	MVCf	0.922*	N.A.	-	-	-	-	-
	MRTDvol	-	N.A.	-	-	-	-0.881	-
	MRTDstim	-	N.A.	0.719	-	-	-	0.732
	Triplet	-	N.A.	-	-	-	-	-
	VA	-	N.A.	0.742	-	-	-	-

* significant (p<0.05) correlation, ^ trend (p<0.1)

Table 4. Correlation coefficients between changes (between t=0 and F2) in scores at tests of functional performance and changes in muscle variables for the non-paretic (NL) and paretic lower limb (PL) of 5 subjects. Berg Balance Scale (BBS), Motricity Index (MI), Functional Ambulation Categories-score (FAC), Rivermead Mobility Index (RMI) and Brunnstrom Fugl-Meyer (FM), Timed ''get-up-and-go'' test (TUG) and 10 meter walk test (10m). Maximal voluntary extension (MVCe) and flexion (MVCf) torque, maximal rate of torque development during voluntary (MRTDvol) and electrically evoked contractions (MRTDstim), triplet torque and voluntary activation (VA).

4.1 Functional performance

From the 5 subjects we followed until F2, subject 1 scored the lowest values of all subjects (n=14) that took part in the study at t=0 at all variables of the paretic lower limb (Table 3), whereas subject 3 scored the best. The actual improvement in the Timed ''get-up-and-go'' test (TUG) between t=0 and F2 may be even greater than presented in Table 2. Subject 1 was not able to perform the TUG at t=0, but during F1 that subject was able to do the TUG in 81 s. Nevertheless, the score of this subject could not be used, since the improvement could not be calculated due to the missing value at t=0. This same subject 1 scored 9 on the Motricity Index (MI) at t=0 but 0 at F1 and F2. Moreover, subject 3 achieved the maximal score of 100 at MI for all three measurement points and only one subject improved between F1 and F2 at this test. This may explain why we found no significant improvement over time for MI in the five subjects who came for these 2 follow-ups.

An improvement of 7%, from 45 to 52% of maximum attainable recovery (n=8) at the Fugl-Meyer Lower Extremity test (FM) was found from ~3.5 months (t=0) to half a year (F1) after stroke (n=8) (Figure 2). For FAC a significant increase from 68 to 88% was found and for MI 47 to 53% (not significant) (Table 2). Kwakkel et al. (2004) similarly observed an improvement from about 62% to 65% at the FM (n=101), 51 to 59% at the FAC and 58 to 59% at the MI during the first half year after stroke. Both the present results and those of Kwakkel et al. (2004) show that most improvement took place within the first 3 months until half year after stroke, as was also found by others (Wade & Hewer, 1987; Jorgeson et al., 1995).

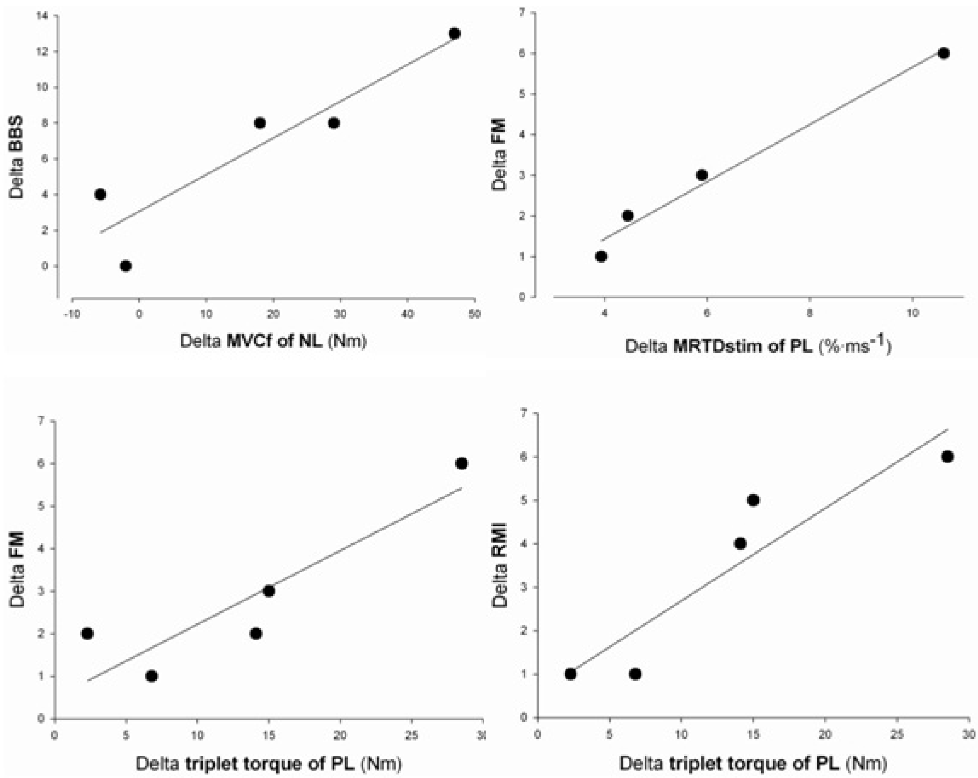
4.2 Muscle variables

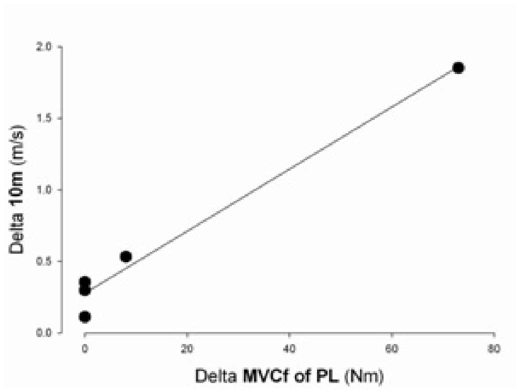
As would be expected after hemiparetic stroke, PL scored consistently lower than NL on the muscle variables (voluntary extension and flexion torque, triplet torque, voluntary activation and maximal rate of voluntary torque development). Variable results in changes in muscle characteristics were found per subject between t=0 and F2 (Table 3). Also in literature there are different results. Carin-Levy et al. (2006) reported, in line with our results, no significant change over time in the strength and muscle mass of both paretic and non-paretic (arm and) leg muscle during the first 6 months after stroke. However, Newham and Hsiao (2001) did observe increased strength throughout the first half year after stroke, while activation failure remained constant. Andrews et al. (2003) showed an increase in both PL and NL knee extensor strength from admission (~2 wk post stroke) to discharge (~4 wk post stroke). So, there are no consistent data indicating that muscle variables improve after stroke.

The main limitation of our study is the small sample size at F2 and F3. Although all new patients with stroke in the rehabilitation centre were examined by physicians, a large number were ineligible for our study, because they had severe cognitive and/or communicative problems, medical complications, no hemiparesis of the lower extremity or, conversely, were too heavily paralyzed and had a previous stroke. A considerable number of patients were not willing to participate (or in case of follow-ups to continue), mainly due to their changed life after stroke and/or the intensity of the protocol. Around half of the eligible patients completed the entire protocol (4 measurement days) at t=0. The scores of stroke severity of our patients (FAC median and quartiles 4 (2.25-4)) confirmed that we managed to recruit a very wide a range of patients with stroke at t=0, but this contributed to the difficulty in statistics, besides the great drop-out of patients during the follow-ups. However, studies with smaller samples sizes than ours have detected significant changes in muscle strength over time in NL (Harris et al., 2001) and PL compared to control (Newham & Hsiao, 2001). Thus, it is likely that, if changes in the thigh muscles of our patients had occurred, these must have been small.

4.3 Correlation between muscle variables and functional performance

The severity of post stroke paresis is related to a person's ability to perform functional tasks; Others found correlations between lower limb isometric knee extension strength and functional performance, like gait distance (Bohannon, 1989) and speed (Bohannon, 1989; Bohannon & Walsh, 1991, 1992; Horstman et al., 2008), sit-to-stand (Bohannon, 2007a; Horstman et al., 2008), transfers (Bohannon, 1988), stair climbing (Bohannon & Walsh, 1991) and balance (Horstman et al., 2008). The new aspect in this study is that we wanted to investigate whether *changes* in functional performance during the first 9 months after stroke related to changes in muscle characteristics.





Δ: delta, changes between t=0 and F2; MRTDstim, electrically evoked maximal rate of torque development; MVCf, Maximal Voluntary Contraction torque of the knee flexors; PL, paretic lower limb; NL, non-paretic lower limb; FM, Fugl-Meyer assessment; BBS, Berg Balance Scale; RMI, Rivermead Mobility Index; 10 m, 10 m walk test.

Fig. 2. Correlations between ΔMRTDstim of PL and ΔFM ($\rho=0.99$, $p=0.01$, $n=4$), between Δtriplet of PL and ΔFM ($\rho=0.90$, $p=0.04$, $n=5$), between Δtriplet of PL and ΔRMI ($\rho=0.92$, $p=0.03$, $n=5$), between ΔMVCf of NL and ΔBBS ($\rho=0.92$, $p=0.03$, $n=5$) and between ΔMVCf of PL and Δ10m ($\rho=0.99$, $p=0.002$, $n=5$).

Most relations were found within subjects between changes in muscle variables of PL and changes in scores at the BBS, a sitting and standing balance measure and the FM, an impairment measure developed to assess physical recovery after stroke (Sanford et al., 1993). Moreover, changes in flexor strength are positively related with changes in the 10m walking speed, which means the more increase in hamstring strength, the bigger the increase in walking speed. In our cross-sectional study (Horstman et al., 2008) strong significant correlations were found between muscle variables of both PL and NL and various tests of functional performance. However, in the present study if we look within subjects, we hardly see any correlations between changes in muscle variables of NL and changes in scores at the functional performance tests over time. This indicates that longitudinal data are essential to gain the required information regarding which (muscle) variables should be trained to induce improvements in functional performance, because cross-sectional data are not exclusive enough.

A question that remains to be answered is what may have caused the improvements in functional recovery? It is suggested that functional gains experienced by patients with stroke are primarily attributable to spontaneous recovery (changes over time that occur naturally) of functional performance of which eighty percent occurs within six months after the onset of stroke (Lind, 1982). Others state that there is some recovery between 1 and 6 months in almost all acute patients with stroke (Wade & Hewer, 1987) and that at 6 months 60% of people with initial hemiparesis have achieved functional independence in daily activities such as toileting and walking short distances (Mayo et al., 1999; Patel et al., 2000.) To facilitate neuroplasticity and cortical reorganization, it would be interesting to also investigate sensory stimulation in future studies with patients with stroke (Nudo et al., 1996; Johansson, 2000) since sensory impairments of all modalities are common after stroke (Carey, 1995). Moreover, sensory deficits are associated with the degree of weakness and the degree of stroke severity related to mobility, independence in activities of daily living, and recovery (De Haart et al., 2004; Lin, 2005). Addressing sensory deficits that accompany muscle weakness may improve impaired processing of afferent signals which in turn may contribute to improved muscle activation, gait patterns, and responses to perturbation during gait and stance (El-Abd & Ibrahim, 1994).

Secondary changes as a result of stroke could be expected in skeletal muscle, e.g. changes in myofiber type (De Deyne et al., 2004) or number and size of motor units. The latter is already reported in the second week after stroke onset (Jorgensen & Jacobsen, 2001). For instance, a change in muscle fiber composition, characterized by selective type II fiber atrophy and predominance of (slow twitch, oxidative) type I fibers has been shown in paretic muscles (Edstrom, 1970; Scelsi et al., 1984; Dietz et al., 1986; Dattola et al., 1993; Hachisuka et al., 1997), which would lead to concomitant changes in contractile speed of the muscle fibers towards those of slow muscles. We can imagine that such a change in fiber type composition can be combated, for instance by training, during the first year after stroke, so that muscle speed characteristics can be restored. Bohannon concludes in his review (Bohannon, 2007b) that resistance training programs are effective at increasing strength in patients who have experienced a stroke but there is no clear evidence for the effect of strength training on functional activities after stroke (Morris et al., 2004). Main results of Saunders' review (Saunders et al., 2004) include only 4 strength training trials (Inaba et al., 1973; Kim et al., 2001; Ouellette et al., 2004; Winstein et al., 2004) and lack nonexercise attention controls, long-term training and follow up. Strength measures were reported to improve after resistance training, albeit without clear benefits for functional performance (e.g. gait speed) (Saunders et al., 2004). Therefore, in addition, the strength training may be combined with task-specific functional training (Sullivan et al., 2006; Hubbard et al., 2009), because it has “the potential to drive brain reorganization toward more optimal functional performance” (Shepherd, 2001). When muscles are weak, isometric contractions can be used in the early stages of rehabilitation as a means of improving the muscle’s ability to contract. However, once muscle strength reaches a certain threshold, exercises should be biomechanically similar to daily life actions in order to be trained to transfer increased force-generating ability into improved performance (Shepherd, 2001).

5. Conclusion

The (small) alterations in the muscle variables correlated well with the improvements in scores on tests of functional performance. Although the correlations do not necessarily imply causality, we think (intrinsic) muscle speed and strength are important variables which can potentially be prolific targets to improve during rehabilitation. It is therefore recommended to investigate the effects of strength training of the thigh muscles during at least the first 6 months after stroke. From such an intervention study on functional recovery it can be elucidated whether increasing strength and speed really improves functional performance.

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